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Swedish resource potential from residues and energy crops to enhance biogas generation

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ABSTRACT

This paper verifies the plausibility of existing assessments of the biogas potential in Sweden and whether a target of 1.1 TWh of biogas for transport, as per defined by Swedish authorities, can be met within the next ten years. We estimate that the Swedish resource potential for biogas generation from residues and energy crops amounts to 8.86 TWh in the midterm, equivalent to around 9% of the current domestic transport energy consumption. A large share of this potential remains unrealized and there is uncertainty regarding the existing resource potential, especially concerning energy crops. Nevertheless, the remaining biogas potential can make an important contribution to meet targets of an increased share of renewables in transport. The study concludes that not only it is possible to meet the increased demand expected for gas in transport until 2020 but the existing potential could justify more ambitious goals than presently set by Swedish authorities.

Contents

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1. Introduction

Sweden has made large efforts to develop alternative energy paths in the past decades. Renewable energy already corresponds to about 47% of the national energy supply, positioning Sweden as the leader in renewables in the whole EU. However, the transport sector is still largely dependent on oil. In fact, only 5.7% of transport fuels were renewable energy sources in 2010 [1]. This share must be almost doubled until 2020 to comply with binding targets in The European Renewable Energy Directive 2009/28/EC (RED). According to RED, the share of renewables in transport has to increase to 10% until 2020 [3]. The projections made by the Swedish Energy Agency (SEA) indicate that the share of renewables in transport shall reach 10.4% in Sweden in 2020, thus meeting EU requirements [4]. Notably, the energy consumption in the transport sector as a whole is expected to increase slowly until 2020 and gradually go down towards 2030, mainly due to increased efficiency in the sector. Biogas and biodiesel (i.e. FAME, Fatty-acid methyl ester), are expected to respond for most of the renewables increase required to meet the target. SEA predicts a demand of 1.1 TWh for biogas alongside with a demand of 0.7 TWh for fossil gas for transport by 2020.

In its upgraded form, biogas can substitute fossil gas and serve as an environment friendly vehicle fuel. As a result of policy efforts, the demand for vehicle gas is growing rapidly in the country [5,8]. However, the realization of the actual potential is evolving slowly and differently for the various biogas sources available [6–11]. The total volume of generated biogas is still rather small, amounting to only 1.1 TWh, of which 53% is used in transport [8]. In the shadow of biogas policies, fossil gas continues growing in importance. Still, a shortage of vehicle gas was experienced at filling stations during 2010 and 2011 [5].

In this context, it is relevant to ask how large the Swedish resource potential actually is from which biogas can be generated in a sustainable way. By sustainable, we mean economically justified, environmentally sound and socially acceptable. Understanding the resource potential available is essential for developing biogas generation in the country and guaranteeing a reliable supply, as well as for defining policies and incentives in this area.

The objective of this paper is to (i) verify the plausibility of existing assessments of the biogas potential in Sweden which are being used to define policies in the sector; and (ii) verify whether a target of 1.1 TWh of biogas for transport can be met within the next ten years.

Meeting the target of 1.1 TWh of biogas for transport would imply doubling present levels of biogas utilization in the country. This amount would correspond to 1.2%of energy use in transport by 2020 and a contribution to the RED target for transport. The RED targets give additional importance to biofuels derived from waste and residues, counting their contribution twice compared to other biofuels [3,4]. Therefore the potential contribution of biogas in meeting the RED targets can be quite significant.

In order to achieve the objective of the paper, we assess the resource potential available to enhance biogas generation in Sweden. We start investigating different types of resources available for biogas generation: urban waste, industrial residues, agricultural residues, and energy crops. The assessment covers the characteristics of the resources, potential for biogas generation, current generation capacity and end-uses in Sweden. Although biogas can be used for different applications, our focus is on biogas for transport as this is the type of application that is boosting the interest for biogas in Sweden. We finally discuss the bottlenecks hindering the realization of the existing potential.

Following this introduction, we introduce the methodology used to scrutinize existing assessments of the Swedish biogas potential. In the third section, we present the characteristics and parameters for calculation of the practical potential of resources for biogas generation, and conclude with our own estimation of the total practical potential. The forth section presents the biogas generation and use in Sweden today and discusses the on-going expansion of generation. In the fifth section, we discuss the gap between resources and realized potential, identifying four main issues that need to be addressed in order to bridge this gap in the next ten years. We then conclude with policy relevant messages.

2. Methodology

Thirteen studies related to biogas potential were identified, which address the resource potential from residues and energy crops for biogas generation in Sweden. Twelve studies were selected and reviewed (see Table 1). One assessment carried out by the Federation of Swedish Farmers (LRF) in 1995 was excluded because LRF published a new assessment in 2005 [12,50]. A content analysis was conducted for the papers evaluated, concepts and resource categories were scrutinized and a cross-analysis of findings was made. Content analysis has previously been utilized by Qu et al. to explore how information of bioenergy was disseminated in China via the internet [15]. Our content analysis of the thirteen studies is focused on the specific context of Sweden, against which we cross-checked the estimations made in each report.

Baxter describes content analysis as a social scientific methodology used to make sense of recorded communication, e.g. technical reports and policy documents [14]. This means that, when evaluating the selected studies, we have looked at who wrote them and for whom. The point here is to understand the perspective of the studies analyzed, the particular interests that motivated them, and the messages being conveyed. These studies on the resource potential available for biogas are supporting decision and policy making. Therefore, the reports can be a way for organizations to position themselves in the public debate. The authors can be commissioned by an interest organization or represent an academic research organization. This must be kept in mind when evaluating the assessments in terms of the assumptions made and the resource potential identified. In addition, we look at how studies are interrelated through referencing.

The analyzed assessments were carried out between 1997 and 2011 by various organizations in Sweden. We carefully review the key assumptions in these various assessments and the estimations made for the different resource categories namely urban waste, industrial residues, agricultural residues and energy crops. Landfill gas has been excluded as it has low methane content and is, therefore, not attractive as a source for vehicle gas. In addition, the volumes of landfill have declined in Sweden as a result of the implementation of waste management regulations in the EU. In scrutinizing the previous assessments, we compare the assumptions

Nomenclature

EPA	Swedish Environmental Protection Agency
EU	European Union
EUR	Euro (currency)
FAME	Fatty-acid methyl ester, biodiesel
GM crops	Genetically modified crops
LNG	Liquefied natural gas
LRF	Federation of Swedish farmers
RED	European Renewable Energy Directive 2009/28/EC
SEA	Swedish Energy Agency

and results with other studies in the European Union (EU). We then complement the data and elaborate our own evaluation of the present biogas potential in Sweden. Thus, our evaluation of the Swedish biogas potential is a product of secondary data generated in previous assessments, complemented by data not considered in those assessments (e.g. average size of certain animal populations), review of assumptions, and re-estimation of the potential for each resource category.

Our analysis clarifies how the potential is calculated for each resource category, and brings new insights about the present potential for each resource category, particularly energy crops which had not been thoroughly evaluated before. Although several studies have attempted to calculate the biogas potential from energy crops, their results are largely divergent, which justified particular attention to this resource category. Throughout the study, we focus on what is practically achievable in terms of biogas production in each resource category in the midterm. Our focus is on biogas that can be upgraded and used as vehicle gas, so we estimate the share of biogas that is likely to be used for this purpose, and the contribution it can make in the energy consumption of road transport in Sweden. Furthermore, we analyze opportunities and constraints to realize the resource potential. We have paid particular attention to the midterm potential. Ultimately, we aim at comparing the resource potential to demand projections and policy targets set for 2020.

A list of selected assessments is presented in chronological order in Table 1 giving an overview of the efforts made in the past years to analyze the biogas potential in Sweden. Key details including authorship, date and focus of the assessments are provided for each assessment.

3. Practical potential of resources for biogas generation

This study uses the resources theoretical potential for biogas generation as a starting point for calculation of the practical potential. The theoretical perspective incorporates all organic matter of a given resource which can be used for biogas generation. In contrast, the practical potential is defined by geography, time dimension, social, technological and economic contexts. This means that we evaluate the practically achievable potential of a resource in a given defined geographical area under specific conditions [27]. For example, the theoretical potential of wet agricultural residues includes all manure that is generated from animal populations, regardless of where it is found and in what quantities. Conversely, the practical potential depends on size and location of animal populations. There are implications regarding logistics and costs if the animal population is kept in a stable or not which, in turn, determines the likelihood of it being used for biogas generation.

For the purpose of our study, resources for biogas generation are divided into four major categories (i) urban waste, (ii) industrial residues, (iii) agricultural residues and (iv) energy crops. This is a typical categorization in many studies.

Notably, there was a significant variation among the various assessments analyzed. Table 2 summarizes the ranges found for each resource category.

As can be gathered from Table 2, there is consensus among the assessments when it comes to the resources available from sewage sludge, industrial residues and wet residues from agriculture. Most divergence is found for the amount of food waste, dry residues from agriculture and energy crops. We now scrutinize the reports, describing their origin and discussing the practical potential for each of the four resource categories.

3.1. Urban waste

In general, waste can be considered non-good, meaning that the economic value of the resource is negative [22]. The urban waste potential for biogas generation includes two main categories. The first is food waste generated by households and other sources, e.g. restaurants and supermarkets. The composition of such waste depends on season, income and location of the source [27]. The second major source of interest for biogas is sewage sludge which is produced by water treatment plants. Another commonly known urban source of waste comes from parks and gardens, but this is not included here because costs for collecting and using these sources are considered too high [19]. Notice that residues from the food industry are not included in this category as they fall under the category industrial residues.

3.1.1. Food waste

Food waste is generated in households, restaurants, big kitchens and also in stores and supermarkets. All these sources add up to 1175 k ton of food waste per year in Sweden measured by wet weight. The largest amount, or 78%, originates from households [19]. An average Swede generates approximately 100 kg of food waste per year [29]. Statistics from the European Environmental Agency show that Sweden produces slightly less municipal waste per capita than the average EU-15 citizen: 515 kg compared to 564 kg in the EU [30]. However, municipal waste includes more than just food waste and the EU statistics do not provide information on food waste specifically to allow further comparison.

The most important factor for determining the biogas production potential from food waste is the degree to which the food residue is separated from other types of waste (e.g., packaging material). In Sweden, 20% of the food waste generated was recuperated in 2008 and the values have improved since then. The Swedish Environmental Protection Agency (EPA), Naturvårdsverket, and the county administrative boards, Länsstyrelsen, have set the target to recuperate 35% of the food waste by 2010. The target has most probably not been reached yet, but is feasible in the near future. In fact, many municipalities that had not had organic waste separation before are now implementing changes in waste management, and this will contribute to achieve the goal.

Fig. 1 illustrates the treatment route of food waste in Sweden. Of the total 1175 kton of food waste generated in the country

Table 1
Previous assessments of production potential considered in our analysis, 1997–2011.

Author	English title*	Reference	Key focus of the analysis
Envirum (Consultancy commissioned by LRF, an interest organization of Swedish agriculturalists)	Biogas from manure and ley crops. Analysis of proposed policy instruments	Biogas från gödsel och vall. Analys av föreslagna styrmedel, Envirum, 2011. [16]	• Analyzes the consequences of proposed policy instruments and subsidies on biogas generation from manure and ley crops. • Provides in-depth analysis of the potential from manure.
Swedish Energy Agency, Swedish Board of Agriculture and Swedish Environmental Protection Agency. (Government agencies)	Proposal to sector wide biogas strategy	Förslag till en sektorövergripande biogasstrategi, ER 2010:23, Energimyndigheten, 2010.[17]	• Discusses government strategies to support biogas • Provides a conservative economic estimation of the existing biogas potential based on prices for vehicle fuel and heat and power.
Swedish Energy Agency (Government agency)	Production and use of biogas in Sweden 2010	Produktion och användning av biogas år 2010, ES2011:07, Energimyndigheten, 2010. [6]	• Annual publication providing data on current generation and use of biogas. • Builds on statistics reported from business organizations representing resource generators.
LRF, EON and Gasföreningen (Interest organizations of agriculturalists, industry and gas business organization)	More biogas. Realization of biogas in agriculture	Mer Biogas. Realisering av jordbruksrelaterad biogas, LRF, E.ON och Gasföreningen, 2009. [18]	• Focuses on the agricultural sector, but also considers food waste (urban waste). • The production potential is built on other assessments regarding agricultural residues and assumptions regarding available land for energy crops. Report includes "total" and "realistic" potential, interpreted as theoretical and practical potential.
BioMil AB and Envirum (Consultants commissioned by business organizations)	The Swedish biogas potential from domestic residues	Den svenska biogas potentialen från inhemska restprodukter, BioMil AB and Envirum, 2008. [19]	• Only domestic residues are considered; energy crops are not included. • In depth study that is often used as main reference. • Builds on an extensive collection of statistics for residues generation.
Lantz et al. (Academic organization)	The prospects for an expansion of biogas systems in Sweden—incentives, barriers and potentials	The prospects for an expansion of biogas systems in Sweden—incentives, barriers and potentials, Energy Policy, 2007. [20]	• Focus on incentives and barriers for production and use of biogas. • Discusses advantages and disadvantages of the different resources. • The potential estimated is based on other reports and detailed in sub-categories of resources.
Pål Börjesson (Research commissioned by government)	Bioenergy from agriculture	Bioenergi från lantbruket, Statens Offentliga Utredningar, SOU 2007–36, Pål Börjesson, 2007 [21]	• In depth study of current biomass production in agriculture and use of agricultural land. Estimates include energy crops and residues. Presents potential for anaerobic digestion and other bioenergy purposes. • Commissioned by government and published as "Official Reports of the Swedish Government" (Swe: StatensOffentligaUtredningar).
Maria Berglund (Ph.D. Thesis)	Biogas from a systems analytical perspective	Biogas from a systems analytical perspective, Ph.D. Thesis, LTH, 2006. [22]	• Makes references to other assessments for theoretical and practical potential from residues and assumes 10% of arable land for energy crops. • Relates production potential to costs of raw material. • Considers the use of digestate as a fertilizer in agriculture.
JTI (Industrial research institute commissioned by Värmeforsk, Thermal Engineering Research Institute)	Biogas – current status and future potential	Biogas—Nuläge och framtida potential, Värmeforsk, 2006. [23]	• Potential study based on previous assessments (SGC & BioMil AB 2005 and JTI 1998) • Contains overview of present technology, discusses different application of biogas and describes on-going development efforts. • Foresees energy crops as the greatest contribution.

Table 1 (*continued*)

Author	English title*	Reference	Key focus of the analysis
SGC & BioMil AB (Business organization and consultancy firm)	Compilation and analysis of the potential for production of renewable methane (biogas and SNG) in Sweden	Sammanställning och analys av potentialen för produktion av förnyelsebar metan (biogas och SNG) i Sverige, SGC and BioMil AB, 2005. [24]	• Considers biogas from anaerobic digestion and thermal gasification • The biogas potential is calculated based on JTI study from 1998, with modifications such as: certain raw materials, e.g. straw, are removed; 10% of arable land is assumed to be available for energy crops which is almost double JTI assumptions, and crops with higher yield are considered.
LRF (Interest organization for Swedish agriculturalists)	Energy scenario 2020 by LRF	LRF's energiscenario till år 2020, LRF, 2005 [12]	• Focus on agriculture and forest. Refers to JTI study for calculation of residues for biogas generation. A large potential – 20 TWh – for energy crops is presented. • Energy Scenario for 2020 dealing with renewable energy potential and markets in Sweden.
JTI (Industrial research institute commissioned by Volvo (vehicle manufacturer) and NUTEK (Swedish Agency for Economic and Regional Growth))	Biogas potential and future plants in Sweden	Biogas potential och framtida anläggningar i Sverige, JTI, 1998. [25]	• Includes an assessment of potential from residues and crops and a geographic representation of the potential. Analyses possible locations for future plants according to plant size and production cost. • Often used as reference. Many subsequent assessments build upon this study. • The institute has specific research on biogas.
Environmental Protection Agency (Government agency)	Agriculture in Sweden 2021	Det framtida jordbruket, 2021, Slutrapport från systemstudien för ett miljöanpassat och uthålligt jordbruk, Naturvårdsverkets rapport nr 4755, Naturvårdsverket, 1997. [26]	• Focus on sustainable agriculture in Sweden in a scenario for 2021 that incorporates several environmental goals and considers low cost options to achieve the goals, including energy crops. • The scenario includes large areas for biogas crops, ley crops, and also for other energy crops, mainly Salix. Foresees the need of subsidies to ley crops for energy purposes. • Many studies, e.g. JTI, use this report as reference, for example to compare assumptions regarding available land for energy crops.

* Our translation of the original Swedish title.

Table 2
Variation of the practical resource potential estimated for biogas generation in Sweden, in TWh.

Resource category	Resource subcategory	Theoretical potential (TWh)	**Practical potential variation**		
			Lower estimation (TWh)	**Higher estimation (TWh)**	**Variation factor**
Urban		2.4 [19]	**0.95 [6]**	**1.6 [24]**	**2**
	Food waste	1.3 [19]	**0.34 [6]**	**0.94 [24]**	**4**
	Sewage sludge	1.0 [19]	**0.61 [6]**	**0.70 [19]**	**1**
Industrial		2.0 [19]	**0.91 [24]**	**1.1 [19]**	**1**
Agricultural residues		12 [19], [25]	**3.6 [24]**	**8.1 [19]**	**2**
	Wet residue	4.2 [19]	**2.6 [24]**	**3.1 [19]**	**1**
	Dry residue	8.1 [25]	**0.98 [24]**	**5.0 [19]**	**5**
Subtotal residues		17	**5.5**	**11**	**2**
Energy crops		70 [28]	**3.3 [25]**	**20 [12]**	**6**
Total		87	**8.8**	**31**	**4**

Note: numbers in brackets refer to the source of the estimated value reproduced here.

annually, only 20% is properly sorted as organic matter. At the end, only 8% of the total food waste generated is used for biogas generation [17,31,33,34]. As much as 80% of the food waste is still mixed with other residues and follow other waste management treatment routes (i.e., incineration or landfilling) [19,31]. Approximately 60% of the sorted food waste goes to composting. An important reason for that is the fact that EPA, the government agency responsible for overseeing actions to substitute deposition

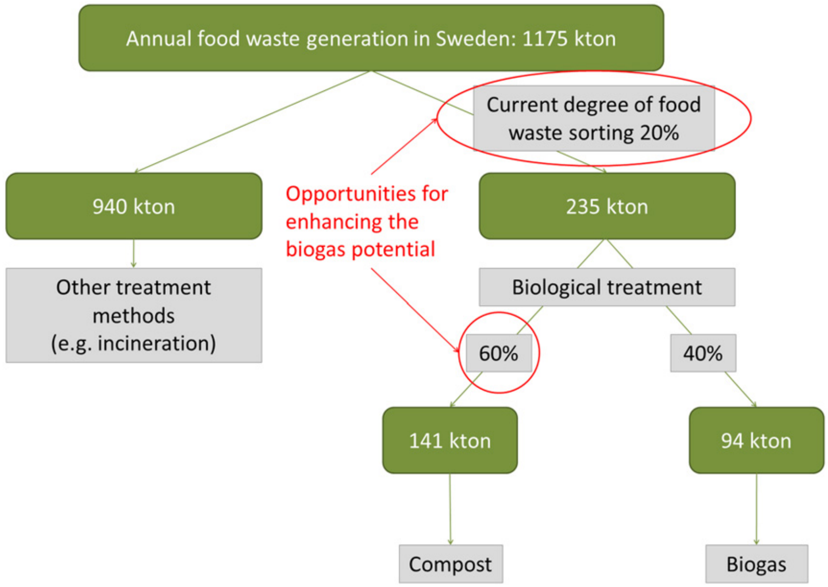

Fig. 1. Food waste sorting in Sweden and opportunities for enhancing the resource potential for biogas generation, 2011.

of organic matter, acknowledges two methods of biological treatment. One acknowledged method is composting of food waste and the other is biogas generation. As a result, composting has been so far the preferred route of most municipalities due to the lower initial investments required.

In our own estimation of the practical potential for biogas from food waste, we assume no use of organic material for composting. We further assume that the goal stipulated by EPA when it comes to food waste sorting is reached, in the short term, as Sweden has a good track record in environmental achievements. For the midterm, we assume that food waste sorting increases to 50% of the total food waste generated. This can be compared with the upper limit which is estimated between 60% and 70%. These assumptions are indicated in Fig. 1 as opportunities to enhance the resource potential. In order to estimate the energy potential, we applied the value of 1.15 GWh/kton of waste. This is an average value for food waste deriving from households, restaurants and food stores [32]. This gives a practical potential of 0.47 TWh biogas from food waste in the short term and 0.68 in the midterm, as opposed to only 0.11 TWh at present.

3.1.2. Sewage sludge

Sewage sludge is a resource obtained directly from waste water treatment plants. This biogas resource is produced at two stages of the sewage treatment process, primary sludge and excess sludge. The first is generated early in the process from the pre-purifier and the latter is obtained during the final process of clarification. Both resources are collected and sent to an anaerobic reactor for bacterial digestion in order to bio-stabilize the organic matter. Biogas is a by-product of the digestion process. Thus, biogas generation from sewage sludge is a natural part of waste water treatment [27]. As a result, this is also the most used biogas source at present.

Two key factors are important when assessing the biogas potential from sewage sludge: the amount of sewage sludge available to be digested, and the biogas yield that can be achieved. For this estimation, the average yield in Sweden has been complemented by data related to available sewage sludge presented in the BioMil AB and Envirum assessment [19]. A total amount of 374 kton of sewage sludge is produced per year, measured as dry matter [10]. The availability of sewage sludge can be enhanced if private sources are transported and added to the public systems. However, the size and location of the plants need to be evaluated since it is not feasible to transport small quantities over large distances [19].

In order to estimate the energy potential, we considered the average yield of current biogas production from sewage sludge, which is 1.94 GWh per kton of sewage sludge. As a result, the sewage sludge potential is 0.73 TWh in the short term.

In the midterm we assume Best Available Technology, BAT, for the digestion process. An increase between 20% and 50% can be achieved applying BAT consisting in process improvements and co-digestion of smaller amounts of fat-sludge [19,35]. We have considered an overall increase of 20% as feasible. As a result, the sewage sludge potential is 0.87 TWh in the midterm. This value corresponds to 57% of the overall potential of urban waste.

3.1.3. Estimated urban waste potential

Our analysis has indicated that urban waste is an attractive resource for biogas generation as these resources are either already collected or on the verge of being collected as a result of present policies. In the midterm, we estimate a practical potential of 1.57 TWh biogas generation from urban waste, 43% or 0.68 TWh from urban waste, and 57% or 0.89 TWh from sewage sludge. We are aware that the realization of this potential will require policy restrictions in relation to organic waste treatment or incentives to make biogas more attractive than composting. However, there is already mobilization in this direction and some incentives for increasing biogas generation have been created. Properly monitored, the biogas route will also generate fertilizers as is the case with composting.

3.2. Industrial residues

Residues derived from industrial processes may have an economic value. Residues differ from waste, which by default is considered a non-good. Despite sometimes having an economic value, industrial residues usually have lower value than the raw material from which they derive [36]. Industrial sectors that generate residues appropriate for biogas generation are, for example, food and beverages, cellulose and pulp & paper industry. Industrial residues may have an alternative use (e.g., fodder or

energy generation other than biogas) which could limit their availability for biogas generation. Otherwise, these residues are logistically attractive as they are frequently available in large volumes adjacent to the plants that generate them.

Usually, industrial residues have higher potential for methane generation than other sources. For example, the average methane content from industrial residues applied for biogas generation in Sweden is 74% compared to 64% for co-digested sewage sludge [8]. However, there is low transparency on information regarding residue generation in industries due to competitive issues and possibly also environmental requirements. This makes the assessment of the potential somewhat difficult.

The practical potential of industrial residues is between 0.9 and 1.1 TWh according to three assessments of the industrial potential (see Table 2). The low information transparency is generally justified as protection of the competitive value of the information. JTI and SGC present the potential aggregated for all sectors, except pulp & paper [24,25]. BioMil AB and Envirum, on the other hand, present disaggregated information on sector level, though little information is provided about where the potential is situated geographically [19]. We have chosen the latter report as our reference case as it provides more details than the others. The practical potential is estimated to reach 54% of the theoretical potential according to the same assessment.

Alternative uses for industrial waste limit the amount of resources available for biogas. In addition, the resource potential for biogas from industrial residues can change over time depending on the relative competitiveness among biofuels. For example, residues from cellulose and pulp & paper industry are attractive for biogas and also for other types of bioenergy.

Recently, a new large industrial-waste-based biogas plant has been granted subsidy by SEA. The plant will make use of the residual waters of a paper mill and will generate 30 GWh per year [37]. This is equivalent to 18% of the practical potential from cellulose and pulp & paper industry according to the BioMil AB and Envirum report [19]. However, the residues from pulp & paper are also attractive for other types of bioenergy. These residues can be used without further processing for heating purposes, meeting internal demand or providing input to local district heating systems. In the near future, competition for forestry resources is likely to increase so that how much will go to biogas depends on the relative competitiveness of this option [38]. Based on this observation, we suggest that the resource potential deriving from cellulose and pulp & paper industry is reduced by 50% (0.085 TWh) in the midterm. It also likely that the potential is reduced with less than 50%, if the relative competiveness of biogas is high. If, e.g., the potential is reduced with only 10% the reduction would be 0.017 TWh and the resource potential deriving from cellulose and pulp & paper industry would be around 0.15 TWh.

In addition to residues from traditionally established industries, increased production of biofuels for transport can generate new attractive residues for biogas. Production of e.g. ethanol generates residues such as Wet Distillers Grain and Solubles, WDGS [39]. Biodiesel production generates residues such as glycerol [19]. These residues are likely to become attractive for biogas generation which can then be integrated in a complete biorefinery complex, finally increasing the total energy efficiency of the plant.

Murphy and Power [39] showed how the energy balance is improved with the use of residues derived from ethanol production from wheat. When applying WDGS in biogas generation, the drying process of the residues can be eliminated. The current use is fodder which requires a drying process. The biogas potential from WDGS deriving from wheat based ethanol is large. The energy content of the residue corresponds to 4.90 MWh per ha of wheat that is dedicated to ethanol production. This implies large potential for biogas generation if ethanol is produced from wheat in large scale in Sweden. 1.30 TWh worth of residues would be obtained if 10% of the arable land in Sweden (260,000 ha) were used for wheat based ethanol production [28,39]. We believe that the additional benefits for the ethanol production process motivate biogas generation, which would then be an expected consequence of increased ethanol production. Small steps towards this development have already been taken in Sweden. The plant Norrköping Biogas, in southern Sweden, has seized the advantages of combined ethanol and biogas production [40].

3.2.1. *Estimated industrial residues potential*

The practical resource potential from industrial residues is estimated at 1.0 TWh. This estimation was done adjusting our reference case, provided by the report from BioMil AB and Envirum, taking into account the increasing competition for forestry resources, as discussed. Therefore our estimation is approximately 0.085 TWh lower than the reference case.

The potential is limited by alternative uses, such as fodder, and competition for industrial residues from other applications of bioenergy. However, this potential could more than double in the midterm, to a total of 2.30 TWh, if energy crops cultivation take off in Sweden. Residues from ethanol production are particularly attractive but residues from biodiesel production also offer opportunities for biogas generation. The latter has not been considered here as biodiesel production has not been significant in Sweden so far.

3.3. *Agricultural residues*

Agricultural residues include crop residues and animal manure. They are obtained from food and fodder production and can be divided in wet and dry residues.

3.3.1. *Wet residues*

Wet residues consist of manure generated from animal populations, primarily cattle, pigs and horses. They are often found in rural areas (e.g., livestock), but also in urban areas (e.g., horse populations) [19,25]. These residues have no direct economic value. When used locally in small-scale biogas plants, there are no extra logistical costs for residue collection [22]. This is because logistical costs related to handling manure will occur even if the residue is not applied for biogas generation. The quantity of wet residues is large, and by-products such as organic fertilizers can be derived from the process of biogas generation. The organic fertilizers are obtained from the digestate, which is the remaining residue after digestion. This by-product contains bio-stabilized organic matter and can provide nutrients for cultivation. Environmental gains also include avoided methane emissions, reduced ground and fresh water pollution, pathogen emissions, nutrients leaching, etc. [22,41].

The key factor when assessing the practical potential from wet agricultural residues is the volumes of resources available. In order to determine the volumes of manure available for biogas generation, one must consider types of animal populations and their size. Assessments available regarding the potential consider various types of animals: cattle, pig, horse, poultry, and sheep [16,19,25]. These populations generate 2716 kton of manure per year, measured in dry matter.

In order to estimate the practical potential, we focus on cattle, pig and horse, which altogether represent 95% of the resource volume [19]. An average horse population contains five animals, while an average cattle population for milk production and an average swine population contain 55 and 487 animals,

respectively [42,43]. Hence, it makes sense, from a logistical point of view, to concentrate the assessment on the two most relevant populations, pigs and cattle, which together comprise 78% of the Swedish potential [19,41]. We followed this rationality in our evaluation of the practical potential and arrived at a volume of 2105 kton of wet residues.

However, the total number of animals of most species has been decreasing in Swedish agriculture during the last ten years. This is particularly the case for cattle and swine. Envirum analyzed the quantities of manure expected to be generated by 2020 [16]. Their analysis is based on different scenarios developed by LRF. In a business as usual scenario, it is assumed that animal populations continue decreasing in size. As a consequence, the cattle population would decrease by 12% and the swine population by 11%. The biogas yield from manure differs between animals. For example, pig manure gives somewhat higher yield than cattle manure. It must also be considered whether the manure is liquid or dry [19].

Our estimation of the biogas potential is based on only two animal populations, cattle and swine. We take into account the projected decrease of these animal populations by utilizing the scenario developed by Envirum. Based on these values, the midterm estimated potential is 2.22 TWh. This corresponds to 69% of the overall potential of agricultural residues.

3.3.2. Dry residues

Dry residues derive from plants in food and feed production. The OECD defines crop residues as "a plant material remaining after harvesting, including leaves, stalks, roots" [44]. In other words, dry residues generated in agriculture are related to cultivation and harvesting of crops. These residues have no economic value but there will be a cost if they are to be recovered for biogas generation, for example, in the fields [22]. In Sweden, there are residues from hay, potato leftovers, potato tops, chaff and husks from crops, which are of interest for biogas generation.

There is a large potential for generation of dry residues in Sweden, which amount to 4807 kton per year measured in dry substance, mostly derived from hay but also from food crops cultivation. At present, the hay residues are often left in the fields as it is costly to collect them [22]. Another problem is that hay residues can be difficult to digest and usually need long residence time in the digester. However, research on hay digestion is on-going and improvements could be obtained in the future [37].

Residues from food crops, mainly potato crops, are attractive from the point of view of biogas production. These residues are easier to digest and logistically easy to obtain. JTI has estimated these resources at 0.98 TWh. Other assessments have estimated the potential of residues from potatoes and other food crops at a similar value. However, the complementary assessments include the potential of hay on their estimation. As a result, the variation between the lower and higher estimations of the practical potential differs by a Factor 5 [19,25].

Our estimation for the dry residues exclusively accounts for the residues from potatoes and other food crops cultivation and it corresponds to 0.98 TWh. This value represents 31% of the overall potential of agricultural residues in the midterm.

3.3.3. Estimated agricultural residues potential

This estimation only includes the most accessible agricultural residues, manure from large animal populations and the most attractive residues from crop cultivation. These have added up to a considerable potential of 3.20 TWh in the midterm.

Part of this potential, mainly wet agricultural residues, is likely to be realized in the short term. This is because a subsidy for digestion of wet agricultural residues is being discussed as part of a national strategy for biogas. The policy is intended to enable biogas generation from sources that give environmental and climate gains, e.g. closing the nutrient cycle and avoiding methane emissions. When it comes to wet agricultural resources, the most attractive part of the potential are found in larger stables and correspond to 0.70 TWh [17]. An evaluation of the possible consequences of the subsidy was carried out by Envirum recently, indicating that a potential between 1.0 and 1.5 TWh could be realized as a result of the subsidy [16]. However, lack of know-how and experience in this area, and low capitalization of agricultural areas could delay the process.

Other subsidies are also being discussed targeting different resources in agriculture (i.e. ley crops). These subsidies can together have a catalytic effect and enable a realization of dry agricultural residues in the midterm, reaching 3.20 TWh biogas from agricultural residues if the planned subsidies are delivered.

3.4. Energy crops

Energy crops are dedicated crops aimed at energy generation. Crops that can be grown and applied in biogas generation in Sweden are, for example, sugar beet, corn, ley crops, and cereals such as wheat. Traditionally, these crops are grown for food or fodder production. Salix is also a common energy crop in the country often used in heating plants. It is important to mention that energy crops can be cultivated on land not used or not suitable for food production (e.g., Salix), an important detail in face of increasing fuel versus food debates.

Energy crops can be used in crop rotation where the cultivation of one crop is sequenced by another, assuring both food production and improved soil quality. For example, ley crop is cultivated on fallow land in Sweden, helping transfer nutrients (e.g., nitrogen) to the soil and foster the recuperation of arable land. Thereby an environmental service is provided when this type of energy crops is cultivated. Ley crops do not compete directly with the production of food crops when cultivated on fallow land. However, they compete for the same land aimed at the production of fodder. As a result, they compete indirectly with breeding of animals and food production.

The Swedish biogas plant Växtkraft in Västerås has opted for ley crops as a complement to organic household waste and fat from restaurant grease traps [45]. The agriculturalists supplying the ley crops receive a high quality fertilizer in return. It is important to stress that crops, if aimed at the production of food or energy, constitute a commodity and often enjoy an established logistical scheme for commercialization.

Of the thirteen assessments analyzed in this study, five made an estimation of the biogas potential from energy crops in Sweden. Key assumptions regarding land area, type of crop and the annual production potential of residues in each assessment are summarized in Table 3. The estimations in these assessments differ by a Factor 6 (see also Table 2). This is primarily due to variations in the assumptions regarding the land available for crop cultivation in Sweden, while there seems to be consensus around the yields (i.e. energy content/area/year).We have, therefore, looked more closely at the potential from energy crops in search for a more accurate estimation.

The five assessments listed in Table 3 use different approaches to estimate available land for biogas crops. In two of them, the land available for biogas crops is considered in the context of overall land availability for energy crops [12,26]. This means that the analyses also consider cultivation of energy crops dedicated to energy generation other than biogas, for example, biofuels or pellets. The other three assessments do not specify the share of energy crops expected to be dedicated to biogas generation [18,24,25]. Instead, all land area contemplated for energy crops

is assumed to be dedicated to biogas crops. This assumption does not consider that energy crops have been used in Sweden for the production of biofuels and pellets for heat plants for some years now. The total land area contemplated for energy crops is considerably smaller than e.g. the land area evaluated by LRF and EPA [12,26]. In either case, biofuel production is likely to increase in the policy context for diversification of transport fuels. Demand from heat plants is currently rather stagnant but biomass demand for CHPs is increasing [2].

The assessment by the Swedish EPA did not provide information on the type of energy crops to be used or their corresponding energy potential [26]. In order to make the information in that assessment comparable with the other studies, we have assumed the same mix of energy crops used by SGC and BioMil AB in their own assessment [24]. Second, three of the selected assessments only specify energy potential without indicating what kind of crops are assumed [12,18,26]. LRF estimates that 20% of arable land can be made available for energy purposes [12]. In this case, land used for export of food crops and fallow land are assumed available for energy purposes. Currently, only 7% of arable land in Sweden is used for food exports and an even smaller area is currently fallow land. The fallow land and the land used for exports of food crops together are, hence, much smaller than the land assumed to be available for energy crops by the LRF assessment [13]. In addition, recent development in food prices could lead to the development of a new scenario in which the actual land available for energy crops is more restricted than initially expected.

Holm Nielsen et al. have evaluated the energy crops potential for EU-27 [41]. In order to allow comparison among different countries, the following parameters were applied: land area, area of agricultural land, area of arable land, share of arable land compared to total area, and arable land per capita. According to these criteria, Sweden has a lower potential for energy crops compared to a European average. For example, Sweden has 0.36 ha of arable land per capita compared to the European average of 0.41. Furthermore, the study assumes that 25% of the energy crops will be used for biogas generation, a more realistic assumption given that various applications of bioenergy are increasing and biogas is not necessarily going to be the most attractive.

Following the analysis of Holm Nielsen et al. Sweden would have 10% of arable land available for energy crops. This number is in line with several of the Swedish assessments revised but lower than the European average [17,23,25,41]. Still considering 25% of the energy crops for biogas, we obtain a land area for biogas crops equivalent to 2.5% of the country's arable land. This value is inferior to what is considered in the five studies presented in Table 3. What biogas potential it corresponds to depends on the types of energy crops chosen.

3.4.1. *Estimated energy crops potential*

Based on the considerations discussed above, we have recalculated the energy potential from energy crops dedicated to biogas based on three key assumptions: (i) available area of arable and fallow land for energy crops; (ii) share of dedicated energy crops which will be used in biogas generation and (iii) varieties of crops cultivated on different land types. Uncertainties related to the two first key assumptions are greater than for the third. The assumptions and resulting potential for arable and fallow lands are specified in Table 4. We base our calculation on the total agricultural area of 2.6 million ha in Sweden as per defined by the Swedish Board of Agriculture for 2008 [28].

We have assumed that ley crops can be cultivated on 50% of the fallow land currently available in accordance with the 1998 study by Swedish Institute of Agricultural and Environmental Engineering [25]. The area of fallow land has decreased since then, because the EU has abolished the quota. We have adjusted the data according to the current areas of fallow land [28].

Table 3
Assumptions and potential found for biogas generation from energy crops in five different assessments.

Source	Assumptions regarding land use	Scenario for	Land area (ha)	Type(s) of crop	Production potential (TWh/year)	Energy crops for other purposes (not biogas generation) considered in assessment
LRF, 2005 [12]	20% of arable land (main part of crops for export and some fallow land)	2020	560,000[a]	–	10–20 "depending on type of crops"	**Yes. Assessment for energy crops in general not specifically for biogas crops.**
Swedish EPA, 1997 [26]	10% of arable land.	2021	280,000	–	7.2[b]	**Yes. Also salix (14% of arable land additionally. Totally 24% of arable land for energy crops)**
LRF, E.ON and Gasföreningen, 2009 [18]	10% of arable land	–	280,000	–	7	**No. Exclusively biogas crops.**
SGC & BioMil AB, 2005 [24]	10% of arable land	–	280,000	Grass, maize, grain, sugar beet incl. tops.	7.2	**No. Exclusively biogas crops**.
JTI, 1998 [25]	6% of arable land + 50% fallow land	2008	170,000	Ley crops	3.3	**No. Exclusively biogas crops.**

[a] The value is calculated from the share of land stated in the report. Report states "between 500,000 and 600,000 ha" to be available for energy crops.
[b] Assuming the same mix of crops as SGC and BioMil AB [24].

Table 4
Potential for biogas generation from energy crops in Sweden.

Assumptions regarding land use	Area for biogas crops (ha)	Kind of crop	Energy yield (MWh/ha)	Potential (TWh)
10% of arable land for energy crops of which 25% are used for biogas [28]	65,000	Grass, corn, grain, sugar beet incl. tops	25.7 [24] (average yield of crops mix)	1.67
50% of fallow land for energy crops of which 100% are used for biogas [28]	73,000	Ley crops	19.4 [25]	1.42
Sum	**138,000**	**–**	**–**	**3.09**

No competition has been considered for ley crops cultivated for energy purposes on fallow land since this land is not as attractive for production of other biofuels. No assumptions have been made regarding availability of new types of energy crops. The yields for mixed crops on arable land and ley crops on fallow land have been obtained from previous studies [24,25].

Our evaluation indicates that there is a considerable potential to generate biogas from energy crops in Sweden, and this can reach 3.09 TWh in the midterm. This evaluation is based on the assumptions that 10% of arable land would be available for dedicated energy crops and that 25% of those would be dedicated to biogas generation. This potential corresponds to 4% of the theoretical potential, which would come from using all agricultural and fallow land in the country for biogas crops [24,25,28].

We further believe that a part of this potential could be realized rather fast if government policy that is under consideration is in fact realized. The policy will subsidize ley crops for biogas generation. The subsidy varies between 450 SEK and 2000 SEK per hectare cultivated, depending on where in Sweden the cultivations are located [16]. SEA estimates the subsidy to enable 0.50 TWh [17].

3.5. Concluding remarks on the Swedish practical potential

Our in-depth review of previous assessments and evaluation of the resource potential for each biogas source indicates a total practical potential of 8.86 TWh for biogas generation from residues and energy crops in Sweden. Our evaluation of the practical potential is more conservative than the ones reviewed and presented in Table 1. For example Lantz et al. mention a potential of approximately 14 TWh. Not all the studies listed in Table 1 are comparable to our result, since we include all categories of residues, and also energy crops on both fallow and arable land. Other assessments, on the contrary, can be limited to only residues or only ley crops on fallow land. Our evaluation indicates a potential equivalent to around 9% of the national domestic transport energy consumption, which reached 96 TWh in 2010 [1]. The majority of the practical potential—71%—is found in the agricultural sector in the form of agricultural residues and energy crops. The remaining 29% is distributed among urban waste and industrial residues. Table 5 summarizes the evaluated resource potential for each one of the sources.

Fig. 2 illustrates the relation between our own estimation and the variation range in relation to the assessments analyzed. The green bar represents our estimation for each one of the resources. The black line pictures the variation range. As expected, variations are largest on the agricultural side, particularly when it comes to energy crops. The potential depends largely on assumptions

Table 5
Resource potential from residues and energy crops for biogas generation in Sweden – our estimation.

Resource category	Midterm potential(TWh)	Share of total biogas potential (%)
Food waste	0.68	8
Sewage sludge	0.89	10
Subtotal urban waste	1.57	18
Industrial residues	1.00	11
Wet residues	2.22	25
Dry residues	0.98	11
Subtotal agricultural residues	3.20	36
Subtotal residues	5.77	65
Energy crops*	3.09	35
Total	**8.86**	**100**

* This value includes minor volumes of dry agricultural residues.

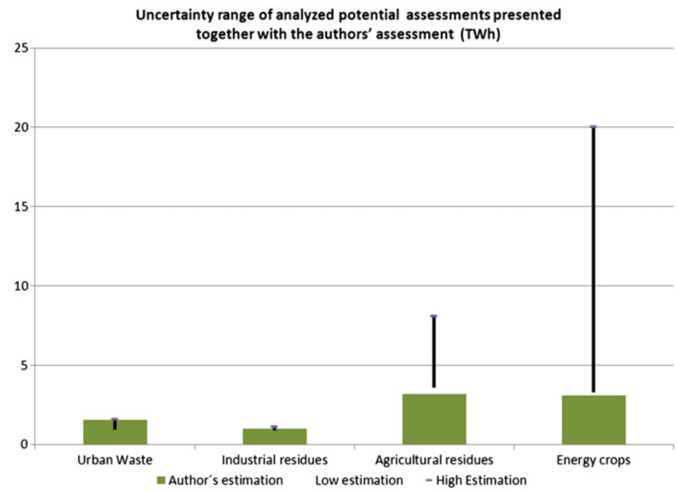

Fig. 2. Variation range of resource potential – Lönnqvist and Silveira—in relation to other assessments.

related to the availability of land for energy crops. Our analysis led us to a more conservative view on what is actually achievable in terms of energy crops for biogas. There is also significant variance when it comes to agricultural residues, which is basically related to logistics and opportunities to realize the existing theoretical potential. On the other hand, variance related to urban waste depends most on the capacity to collect food residues in a more efficient way and here we see that a large potential can be actually realized. Even if it may take some time to organize the collection of waste properly, there is already mobilization in this direction.

4. Biogas generation and use in Sweden

In 2010, approximately 8.6 million tons of resources – measured in wet weight – were used for generating 1.09 TWh biogas in Sweden [6]. This corresponds to 12% of the practical potential estimated in the midterm. Fig. 3 shows the contribution from each resource category in biogas generation. The flows represented are those larger than 500 t. Other minor flows also exist but have been excluded from the overall representation as they account for less than 0.01% of the total resource mass used in biogas generation.

As illustrated, urban waste constitutes the largest volume of resources followed by industrial residues. Agricultural residues and energy crops contribute a much smaller volume in current generation activities, despite the significant potential [6]. Fig. 3 also indicates the biogas generation processes in use, which were divided into four plant categories: (i) co-digestion plants, (ii) farm-based plants, (iii) biogas plants at sewage treatment sites, and (iv) biogas plants in industry. Landfill gas has been excluded as it is not within the scope of our study.

Co-digestion plants apply all four resource categories in generation in rather equal proportion. Farm-based plants, on the other hand, receive industrial residues as a complement to agricultural residues. Surprisingly, according to the statistics of the SEA, no energy crops are digested in farm-based plants. Biogas plants at sewage treatment sites mainly use urban waste but receive also industrial residues and energy crops to generate biogas. Contrasting to the other generation categories, biogas plants connected to industry do not use other than industrial residues [6]. Table 6 shows how the generation was distributed among the four plant categories.

As shown in Table 6, biogas plants at sewage treatment sites are the major biogas source in Sweden, responding for 56% of the present

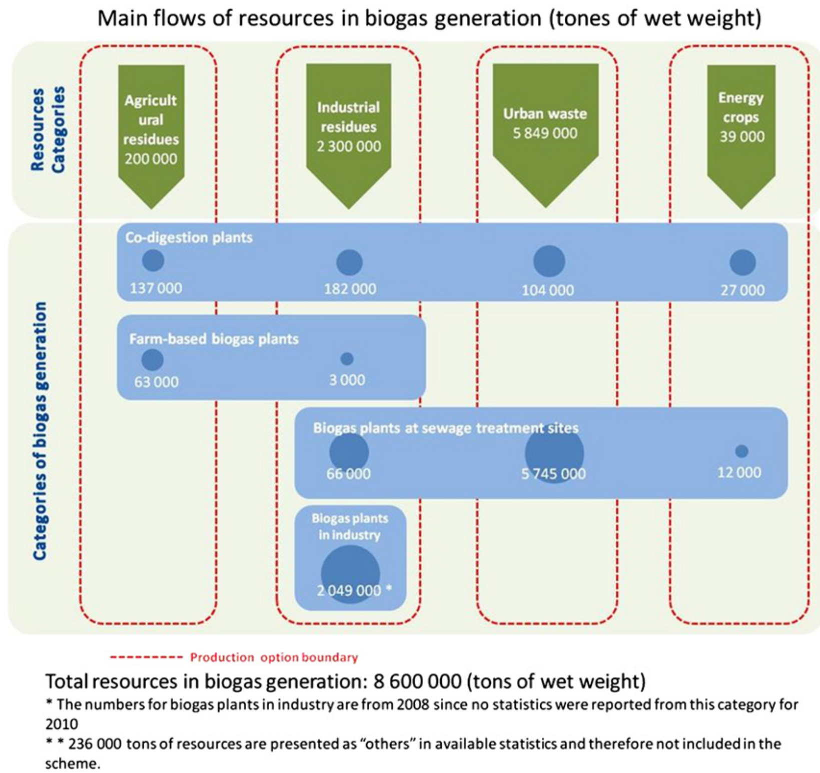

Fig. 3. Main flows of biomass resources for biogas generation in Sweden.
Data Source: SEA [6].

Table 6
Biogas generation in Sweden, 2010.

Biogas generation category	Number of plants	Generation (TWh)	Share (%)
Co-digestion plants	18	0.344	32
Farm-based plants	14	0.016	1
Biogas plants at sewage treatment sites	135	0.614	56
Biogas plants in industry	5	0.114	10
Sum	**172**	**1.088**	**100**

biogas generation. Generation in this category is also distributed over a large number of plants, 135 units. The second largest category is co-digestion plants, followed by biogas plants in industry. The smaller contribution comes from farm-based plants. At present, there are only fourteen farm-based plants in Sweden generating merely 0.02 TWh [6].

However, the distribution among biogas generation categories is continuously changing as new plants, often supported by government subsidies, are commissioned. SEA has distributed 142 million SEK (ap. 16 million Euros) during 2010 and 2011 as investment support to 18 projects. Among these, a large scale plant based on pulp and paper residues stands out. The plant is built by StoraEnsoFors AB, a company in the forest industry. But also plants based on urban waste, agricultural residues and energy crops are being built [37].

The investment costs of biogas facilities give an indication of the opportunities to enhance profitability among the biogas generation categories. Attention has been given to co-digestion and farm based biogas plants. The former is a quickly growing category while the latter is not growing significantly in spite of a significant resource potential available. Investment costs for co-digestion is typically around 510 EUR/ton of feedstock according to AvfallSverige who studied a number plans for biogas plants. These figures refer to wet digestion technology receiving household waste and other semi-liquid waste [46]. Wet digestion is currently the dominant technology in Sweden. However dry digestion is also an option. A recent budget offer from a German–Italian technology provider to a Swedish biogas producer indicated an investment cost of 225 EUR/ton for a facility which receives 25 000 t per year [47]. SGC has studied the investment cost for large scale (100–260,000 t/year) farm based plants [48]. Their study contemplates Swedish conditions and builds on German experiences. Only the digestion facilities would cost between 890 and 3000 EUR/ton to build. It can be seen that the estimated investment costs are considerably higher for farm based plants compared to co-digestion plants. It can also been seen that the investment depends largely on the choice of technology. However, it can be expected that costs drop as plants are built and learning occurs. This has been seen not least in Danish biogas sector [49].

In 2010, 0.57 TWh or 53% of the generated biogas in Sweden was consumed as vehicle gas in the transport sector [6]. This share has increased rapidly from only 20% in 2005 [11]. In 2010, the second largest application was heating, where 34% of the biogas or 0.37 TWh was consumed. Of the remaining biogas generated, 4% was used for electricity generation and 8% was flared [6]. The share of biogas flared is decreasing but still significant and indicates an immediate potential for enhancing biogas use by redirecting the flared gas to energy services. Biogas generation sources and the final gas applications for Sweden are illustrated in Fig. 4. Notice that the scheme in Fig. 4 presents an energy generation approximately 0.3% lower than the one presented in Table 6 which is due to some data gaps.

As shown in Fig. 4, biogas generated from plants in industry is used mainly for heating purposes. On the other hand, biogas derived from sewage treatment is often upgraded but also used in heating. Biogas originating from co-digestion plants is mainly upgraded. Biogas plants at sewage treatment sites and co-digestion plants

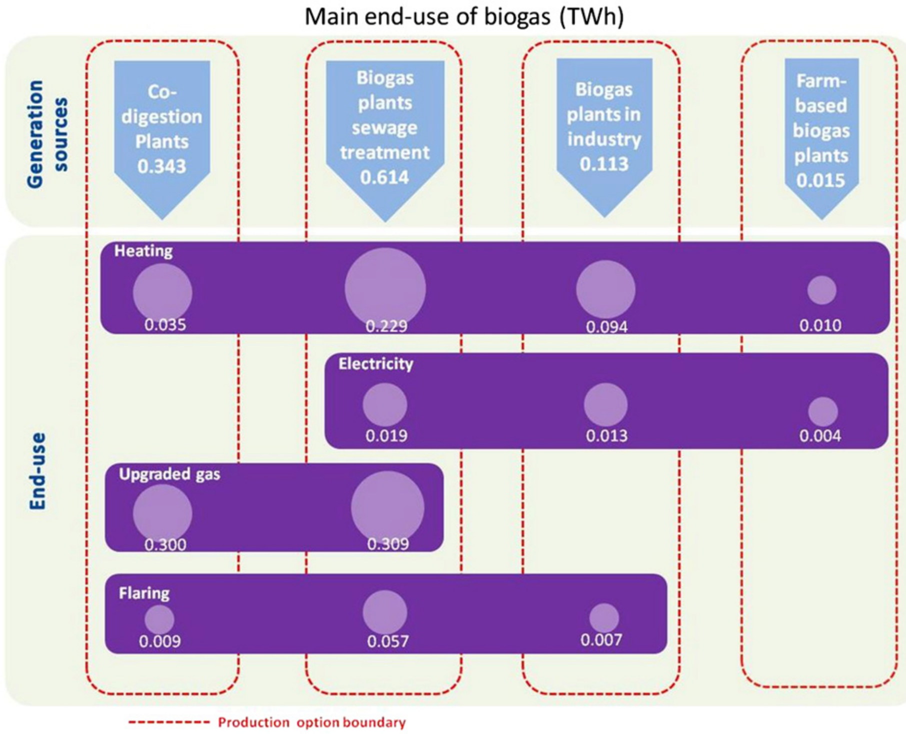

Fig. 4. Main end-use of biogas in Sweden (in TWh).
Source: SEA [6].

produce more than 99% of the biogas that is being upgraded. Of the upgraded gas 94% is used as fuel in the Swedish transport sector. The share of generated biogas that is being upgraded is quickly increasing [6].

Vehicle gas is already the largest application of biogas in Sweden but its volume is still not enough to fulfill the national demand, and thus needs to be complemented with fossil gas. Sweden does not have fossil gas sources but imports started in 1985, initially targeting industrial applications. Vehicle gas has been sold since 1995. Initially, only fossil gas was used, but biogas is now the main source of vehicle gas. The market development for vehicle gas in Sweden from 1995 to 2010 is illustrated in Fig. 5. Sweden expects to achieve its EU-RED target partly using biogas as vehicle fuel.

Supply of fossil gas has stimulated the expansion of a gas vehicle fleet and the market for vehicle gas. In the period between 2005 and 2010, the number of gas-driven cars increased by 332%, busses by 81%, and heavy vehicles by 119%. By the end of 2010, there were more than 32,000 gas vehicles in the country [5]. This development also created conditions for the deployment of biogas. Approximately 93 million Nm^3 of vehicle gas were sold in 2010 which corresponds to 0.94 TWh. Fig. 5 shows that whilst the demand for vehicle gas continues growing, the sales of fossil gas stagnated between 2007 and 2009. That situation changed in 2010 as new infrastructure for fossil gas supply came into place. The future contribution of biogas and fossil gas in the total national demand is presently subject to debate. The government suggests that biogas will gradually substitute fossil gas fully [51]. However, that might not be the case in face of the large infrastructure development for fossil gas imports that is already in place.

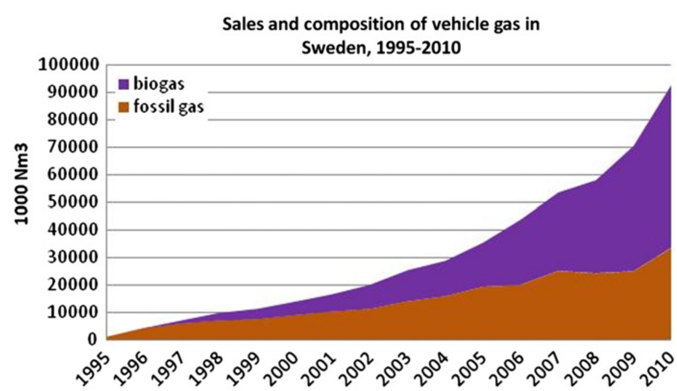

Fig. 5. Sales and composition of vehicle gas in Sweden, 1995–2010.
Source: Gasföreningen [5].

Since policies are being designed to promote biogas generation and use, these gaps need to be addressed in order to support effective policies, and better promote and monitor improvements. This includes reviewing information standards, improving the biogas generation cycles (i.e. using digestate as fertilizer) to optimize resource yields and process economy, clarifying the relations between resource availability and competition (i.e. land), and improving logistics along the resource supply chain (i.e. food waste sorting). Following from our analysis, we have identified five specific issues related to the resource potential and the production processes which require some immediate attention.

5. Bridging the gap between resources and implementation

There is a gap between the resource potential available in Sweden and the actual generation of biogas achieved so far.

5.1. Data gaps

Following from our in-depth analysis, we have identified some data gaps that affect the development of the biogas segment. These data gaps make the definition of policies for the biogas

segment and their monitoring quite difficult and may lead to false ideas about resource availability and the actual potential for biogas generation in the country. Ultimately, this could compromise the goals set up for the transport sector.

We estimate the potential for biogas generation in Sweden at 8.86 TWh in the midterm, considering four major resource categories. Official data, however, organizes the data according to generation categories not the resource base. According to statistics provided by SEA, approximately 1.09 TWh of biogas generation has been achieved [6]. This corresponds to 12% of the assessed potential. While 88% of the potential remains unrealized, it is not completely clear how it is distributed due to the format of statistics available. Any attempt to determine the degree of use of a specific resource can only be an approximation.

In order to tackle the mismatch and understand the distribution of the potential yet to be realized, we have compared the available information. Fig. 6 illustrates the comparison between midterm resource potential and resource utilization in 2010. The degree of utilization represented is an approximation because different generation categories are compared to, or attributed to, different resource categories. For example, biogas plants in industry are attributed directly to industrial residues. Further, generation from biogas plants at sewage treatment sites and co-digestion plants are attributed to urban waste resources. Finally, farm-based plants are attributed to agricultural residues and energy crops.

From the comparison presented above, it appears that 61% of the potential available in urban waste and 11% of the industrial residues are already being used for biogas generation. Conversely, the realization of resources in agricultural activities – agricultural residues and energy crops – is not visible in the figure because of the small generation in farm-based plants. In reality, the degree of utilization of urban waste is lower and the degree of utilization of industrial residues is higher. This is because industrial residues are also used in co-digestion plants, which are attributed to urban waste in this comparison. Hence, it is not trivial to determine how much room there is for increased generation based on a given resource category.

The statistics of biogas generation should therefore be complemented by a different data format which could be based on resource availability and, possibly, its location. This database should contain more detailed information regarding use of resources in the generation process. Such a data format could indicate opportunities for generation expansion more clearly and, thereby, better assist decision-making processes.

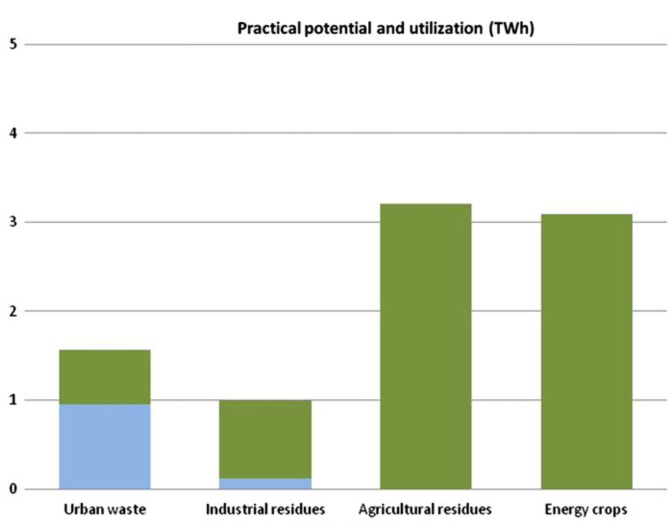

Fig. 6. Comparison between the authors' estimation of practical midterm potential and utilization of resources in 2010 [6].

5.2. *Opportunities for co-digestion*

Regarding biogas plants at sewage treatment sites, Lantz et al. discuss an available overcapacity in such plants [20]. This could imply an opportunity to increase biogas generation. However, it cannot easily be quantified and evaluated due to lack of appropriate data. Additionally, we see obstacles which have to be solved in order to make use of the overcapacity.

One problem related to biogas plants at sewage treatment sites is finding an output to the digestate. Presently, digestate from sewage sludge is not recommended by LRF for agricultural use because it is an unreliable source when it comes to contaminants, as opposed to the digestate from other types of plants, for example based on agriculture residues [22]. A possible solution is to use the digestate in energy crops such as Salix. However, the opportunity to increase the use of digestate from sewage plants is limited for this application since 65–70% of the Salix cultivation area already receives digestate [52]. Incineration of the sewage sludge is another option, but the fertilizing qualities are then lost. Thus the overcapacity available in biogas plants located at sewage treatment sites is not only difficult to quantify, but its realization might also be hindered by the lack of attractive output value for the increased amount of digestate generated in the process.

Co-digestion is a possible alternative for using the overcapacity available in sewage plants. While the opportunity to increase the use of digestate in Salix cultivation is limited, other energy crops could be targeted. An increased production of energy crops could absorb the volumes of digestate deriving from sewage sludge. Energy crops are not part of the food chain and, hence, different requirements could be applied on the fertilizer, similar to the case of Salix production. Increased production of energy crops, e.g. wheat for ethanol or ley crops for biogas, could absorb the digestate and hence allow co-digestion to expand, making use of the available overcapacity in the biogas plants at sewage treatment plants. Improving the synergies between biogas plants at sewage treatment sites and energy crops require a joint strategy for enhancing energy biomass sources and biogas generation.

In addition, the yield of biogas plants located at sewage treatment sites can be increased by 20–50% [19,35]. This can be accomplished through process improvements and co-digestion with smaller amounts of fat-sludge, which does not affect the amount of digestate output significantly. This is a good first step alternative for the sector to improve process efficiency without having to find an outlet for increased digestate output. However, it should be noted that biogas plants at sewage treatment plants in Sweden are not built primarily to generate biogas but to reduce the volume of sludge [53]. This means that biogas yield might not be prioritized. In brief, there is an opportunity to increase biogas generation through making use of over capacity at existing biogas plants at sewage treatment sites, but also a bottleneck in the form of digestate generated from these plants for which solutions can be found in increased energy crops cultivation. A significant gas yield increase can also be achieved through technical improvements.

5.3. *Promoting energy crops*

Inspite of the large existing potential for biogas generation from energy crops and agricultural residues, only a small share of these resources has been realized so far. The generation in farm-based biogas plants is still insignificant, and the volume of energy crops which are used in co-digestion plants is rather small.

This situation could be about to change as a result of recently suggested subsidies for cultivation of ley crops.

Meanwhile, resource competition has been a much discussed issue in the food versus fuel debate and this may result in limited availability of land for energy crops. In fact, energy crops cultivation has not fully taken off in Sweden. Energy crops for biogas are limited: less than 0.5% of the total raw material applied in biogas generation during 2010 came from crops [6]. Small volumes of wheat-based ethanol are also produced in Sweden, and the production is often combined with biogas generation. The domestic production of biodiesel is almost negligible [54]. The area of arable land that we estimated available for energy crops is in the magnitude of the area used for Swedish crop exports. This is because we assume that Sweden could produce food and fodder in a similar proportion to what is consumed in the country today and also dedicate land resources for energy crops.

However, it is possible to increase efficiency and also reduce competition for land and other resources which might occur as a result of increased cultivation of energy crops. Measures can be taken to increase the yield of energy crops (i.e., energy content/area/year). This means that more energy can be obtained from less land area. New crop varieties and cultivation practices can be introduced in which crops are harvested before they are ripe, which in some cases permits multiple harvests per year and more appropriate digestion technologies can be deployed [17,20,55].

A long-term opportunity to increase the yield of biogas crops could be cultivation of genetically modified crops (GM crops) [57]. This would increase the yields of energy crops (non-GM crops) and reduce risks of competition for land and other resources. Experiments using GM crops for food production are already taking place in Sweden. There are also rules in place for use of GM crops even though some issues, e.g., regarding co-existence between GM crops and non-GM crops must still be sorted out according to the Swedish Board of Agriculture. A permit is always required when cultivating GM crops [56]. The question remains open as to how long acceptance for a larger use of GM crops may take.

5.4. Enhancing profitability

The issue of economic attractiveness of biogas is related to the generation and upgrading processes and also to competition for resources. Though biogas generation has increased in Sweden in the past few years, profitability is still perceived as a problem [17,59]. The conditions for biogas generation expansion differ among the generation categories. While co-digestion and industrial plants grow quickly, biogas plants at sewage treatment sites are only growing at the margin. The slow growth also occurs in farm-based biogas plants despite their large unrealized potential [6–11].

Additional profitability problems are seen in the upgrading process. Before biogas can be used as vehicle gas, a process of upgrading is necessary [27]. Inspite of the high market price for upgraded biogas as a fuel, its economic feasibility related to upgrading process is not assured. This is because the costs of upgrading biogas are still high. According to SEA, while the market value of upgraded gas increases by Factor 2, the costs of generation increase by Factor 3–5, compared to heat and power applications [17]. Hence, realization of the resource potential might not necessarily leads to more biogas for transport uses.

Profitability is a problem particularly for energy crops dedicated to biogas generation. Previous studies indicate that biogas crops are less competitive than bioethanol and biodiesel crops and a scenario where biofuel crops prevail over biogas crops is more likely to evolve [17,20]. Nevertheless, such a scenario could be still beneficial for biogas generation because the generation of these biofuels produces residues, which are attractive for biogas generation (e.g. wet distillers grain and soluble from ethanol generation and glycerol from biodiesel generation) [19,39].

SEA, Swedish Board of Agriculture, and EPA have jointly proposed a sector wide strategy for biogas, which incorporates direct subsidies for generation of biogas from two specific resources, wet agricultural residues and ley crops [17]. The subsidies are especially motivated by the environmental and climate gains derived from biogas generation. For example, spontaneous methane emissions from manure would be mitigated through digestion of wet agricultural residues. When it comes to ley crops, the proposed subsidy is actually an extension of an existing subsidy applied to fodder. The motivation is that the environmental gains, or environmental services, of cultivating ley crops are maintained independently of it being used for fodder or energy [17]. Although the strategy is focused on two resources, it creates opportunities to apply other resources through co-digestion using the subsidized infrastructure. As a result, this strategy can be perceived as a catalyst for using other resources related to agricultural activities (i.e. dry residues and energy crops other than ley crops).

More than 70 organizations have submitted comments on the strategy. The Ministry of Enterprise, Energy and Communications is now compiling the received comments for presentation to the ministers of Enterprise, Agriculture, and Environment. The strategy concerns different political areas and different stakeholder groups. Therefore, different parts of the strategy are approved by different Ministries. If approved, this will be a new example of cross-sectorial policies designed to promote biofuels.

5.5. Opportunities and constraints to be tackled

The opportunities and constraints to increase biogas generation in Sweden are summarized in Table 7. We have firstly considered those opportunities for which no new policies, regulations or infrastructure are needed. We have also considered actions that may require new, but not too extensive or complex, infrastructure, policies or regulations. For example, the planned policy incentive for utilization of wet agricultural residues is considered to be introduced soon since the policy preparation is already in an advanced stage. We further consider an enhancement of the food waste potential feasible since an increase is already happening as a consequence of various initiatives at municipal levels.

Table 7 summarizes opportunities that are right at hand to increase biogas generation from various resource categories in Sweden within the coming ten years. For the midterm, we can see a potential equivalent to 8.86 TWh readily available for realization. If we compare the present generation to the midterm potential, only 12% has been realized, of which 53% is used for vehicle gas.

In the short-term, we may observe an expansion of the gas vehicle fleet, which can initially be fueled with increased biogas generation. However, ambitious policies stimulating gas demand could also forge a safe market for imported fossil gas. In the medium and long-term, this may lead to increased use of fossil gas in the transport sector crowding out biogas generation on a cost competitive basis, especially if the identified gaps are not bridged. In fact, it appears that biogas demand for transport helps motivate investments in fossil gas infrastructure. The new infrastructure built close to the capital, in Nynäshamn, consists of a liquefied natural gas (LNG) harbor and a large storage capacity (20,000 m^3 LNG) that could serve as a first platform to enable more imports of fossil gas to Sweden [58].

Table 7
The Swedish biogas potential in the midterm – opportunities, constraints and actions to be taken.

Resource category	Opportunity at hand for biogas generation	How?	Constraints	Actions to be taken
Urban waste: food waste current degree of use: Low	Increasing the resource potential up to a total of 0.27 TWh.	The majority of the recuperated food waste is presently composted but could be used for biogas generation.	Municipalities can presently choose between digestion and compost for biological treatment of residues. Infrastructure for digestion requires higher initial investment compared to infrastructure for composting.	Target biogas generation specifically offering incentives for municipalities to choose biogas instead of composting
	Increasing the resource potential up to a total of 0.68 TWh.	The degree of food waste recuperation is increasing as a result of municipal efforts to meet the goal set by EPA, and the county administrative boards. The current degree of 20% is expected to increase to 35% in the short term. We estimate that 50% is achievable in the midterm.	Environmental targets regarding food waste sorting are still not fulfilled in many municipalities. Lack of incentives, proper logistics and infrastructure to sort and collect food waste for biogas generation in many municipalities. Total volume of food waste may decrease as public awareness increases	Enforce binding targets for the municipalities regarding food waste recuperation. Organize food waste collection to facilitate meeting the target and support infrastructure investments for expansion of biogas generation. Gradually increase environmental targets from the current level of 35–50% in the midterm.
Urban waste: sewage sludge current degree of use: high	Increasing the energy yield up to a total of 0.89 TWh.	The yield in biogas generation at sewage treatment plants can be increased 20–50% by applying best available technology and process optimization on existing plants.	Biogas plants at sewage treatment plants in Sweden are built mainly to reduce the volume of sludge. Maximizing biogas generation might therefore not be prioritized	Support investments to upgrade biogas plants at sewage treatment plants. Support innovation and research to improve generation capacity.
	Optimizing the use of already installed capacity	An overcapacity exists at many biogas plants at sewage treatment sites. This could be used to co-digest sewage sludge with waste, residues and energy crops. In some cases a better yield can be obtained through co-digestion, compared to digesting raw materials individually.	The size of the overcapacity is hard to quantify due to limited information. Digestate from sewage sludge is generally not accepted as biofertilizer due to contaminants. Additional digestate output could be difficult to commercialize.	Define joint strategy for biogas plants at sewage treatment sites and energy crops. Digestate could be s used in energy crops.
Industrial residues current degree of use: low	Increasing the resource potential up to a total of 2.4 TWh.	Residues from liquid biofuels, e.g. bioethanol and biodiesel can be used for biogas generation, if production of these biofuels increases in Sweden. A production of ethanol from wheat cultivated on 10% of the agricultural land would generate industrial residues suitable for biogas production corresponding to 1.3 TWh.	Competition for land and other resources for production of biofuels, food and fodder	Promote biofuel production and biogas generation of residues through support for investments, innovation and research.
Agricultural residues: current degree of use: insignificant	Planned policy incentive enabling 0.70 TWh.	A subsidy for digestion of wet agricultural residues is planned in the national strategy for biogas. The policy is foreseen to enable biogas generation of the most attractive part of the potential which is found in larger stables. The production subsidy will give ap. 0.02 euro/kWh of biogas generated from wet residues. The subsidies proposed can further act as catalyst to promote the development of infrastructure. With that in place, dry agricultural residues could be co-digested	Profitability, lack of know-how and practice with biogas generation from agricultural residues.	Implement policy incentives proposed in biogas strategy (methane reduction subsidy for digestion of wet residues). Upscale production through incentives for new investments
Energy crops current degree of use: insignificant	Planned policy incentive enabling 0.50 TWh.	A subsidy for digestion of ley crops is planned in the national strategy for biogas. 0.50 TWh is expected to be enabled by the subsidy, which also includes dry residues.	Competition for land and other resources for production of biofuels, food and fodder	Realize planned policy incentives in biogas strategy (extension of support for ley crops).
	Increasing the energy yield with new varieties of energy crops and new practices.	An increase of yield can be obtained with right choice of energy crops as opposed to applying traditional food or fodder crops. Biogas crops can be harvested before they are ripe, which in some cases permits multiple harvests per year.	Lack of established biogas generation chain based on energy crops.	Support innovation and research in the field. Joint strategy for energy crops and biogas plants at sewage treatment sites.

6. Policy relevant messages about the biogas potential in Sweden

Biogas is still a marginal energy carrier in Sweden. We have estimated the practical resource potential to generate biogas in Sweden at 8.86 TWh in the midterm based on the analysis of four types of resources: urban waste, industrial residues, agricultural residues, and energy crops. Our estimation contrasts with other more optimistic studies. For example Lantz et al. estimated a potential of approximately 14 TWh, without considering new technologies. In any case, there is a significant potential of resources which allows for a large expansion of biogas generation in Sweden.

So far only 12% of the midterm potential for biogas generation, or approximately 1.09 TWh has been realized in Sweden, of which 53% or 0.57 TWh is being used for transport. But this is changing rapidly. The demand for biogas in transport is increasing fast, requiring complementation with fossil gas. The current relation is 64% biogas and 36% fossil gas. SEA predicts a supply of 1.1 TWh of biogas for transport by 2020, together with a supply of 0.7 TWh of fossil gas. This implies a relation of 61% biogas and 39% fossil gas in transport. Thus biogas is projected to reach twice the present levels. Meanwhile, the share of fossil gas is projected to remain almost the same.

The objective of this paper was to verify whether a target of 1.1 TWh biogas for transport can be met in the midterm, that is, within the next ten years. We have shown that this can be achieved with good margin given the large resource potential readily available. No major energy breakthrough is necessary for that but policies are required to trigger investments. In fact, the existing potential far exceeds the demand projected by SEA and *could cover the entire demand for vehicle gas projected for 2020*. Hence, a scenario where fossil gas in transport is entirely replaced by biogas is theoretically feasible. In practice, this is not likely to occur by itself given a number of barriers. In addition, the infrastructure that has been put in place for fossil gas may delay the penetration of biogas. In any case, it is surprising that the goals for biogas utilization have such low ambition level.

Being part of the EU, Sweden has mandatory targets for the introduction of renewable energy in transport. The RED targets give additional importance to biofuels derived from waste and residues, counting their contribution twice compared to other biofuels. Therefore, the potential contribution of biogas in meeting the RED targets is quite significant.

For the opportunities of increased biogas generation to be realized, gaps need to be addressed. In particular, a large but yet unexploited potential exists in the form of energy crops and agricultural residues. The subsidy for ley crops and wet agricultural residues suggested by SEA, Swedish Board of Agriculture, and EPA could change this situation. The subsidy could enable the development of infrastructure for generation of biogas from these resources and also act as a catalyst for other resources. In order to accurately evaluate these opportunities for generation expansion complementary data is needed so that incentives can be designed according to the actual distribution of the remaining potential.

Thus, it is possible to avoid increased fossil gas use in transport and even substitute it with renewable sources in the midterm in Sweden. The remaining biogas potential can make an important contribution to meet targets of an increased share of renewables in transport by 2020. The goals and targets of renewables in Swedish transport sector, particularly regarding biogas, could even be more ambitious to harvest the considerable potential available in residues and energy crops.

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References

[1] Energiläget 2011, (Energy in Sweden – facts and figures 2011), ET 2011:42, Swedish version available for 2010. Available from: www.energimyndigheten.se; 16-11-2011.
[2] Energiläget 2010, (Energy in Sweden – facts and figures 2010), ET 2010:46. Available from: www.energimyndigheten.se; 15-12-2011.
[3] The European parliament and the council. Directive 2009/28/EC of the European parliament and of the council. Official Journal of the European Union; 23-04-2009.
[4] Swedish Energy Agency. Långtidsprognos 2010, ER 2011:03; 2011.
[5] Swedish gas association (Gasföreningen), Homepage. Available from: www.gasbilen.se; February 17, 2010 and November 16 2011.
[6] Swedish Energy Agency. Produktion och användning av biogas år 2010, ES2011:07; 2011.
[7] Swedish Energy Agency. Produktion och användning av biogas år 2009, ES2010:05; 2010.
[8] Swedish Energy Agency. Produktion och användning av biogas år 2008, ES2010:01; 2010.
[9] Swedish Energy Agency. Produktion och användning av biogas år 2007, ES2010:02; 2010.
[10] Swedish Energy Agency. Produktion och användning av biogas år 2006, ER 2008:02; 2008.
[11] Swedish Energy Agency. Produktion och användning av biogas år 2005, ER 2007:05; 2007.
[12] LRF. LRFs energiscenario till år 2020; 2005.
[13] Mayring P. Qualitative Inhalts analyse. Weinheim: Deutscher Studien Verlag; 1997.
[14] Baxter J Content Analysis. International Encyclopedia of Human Geography; July 2009.
[15] Qu M, Tahvanainen L, Ahponen P, Pelkonen P. Bio-energy in China: content analysis of news articles on Chinese professional internet platforms. Energy Policy 2009.
[16] Lantz M, Björnsson L. Biogas from gödsel och vall. Analys av föreslagna styrmedel. Envirum March 2011.
[17] Swedish Energy Agency. Förslag till en sektorsövergripande biogasstrategi, ER 2010:23; 2010.
[18] LRF, E.ON and Gasförningen. Mer Biogas. Realisering av jorbruksrelaterad biogas; 2009.
[19] BioMil AB and Envirum. Den svenska biogaspotentialen från inhemska restprodukter. Lund; 2008.
[20] Lantz M, Svensson M, Björnsson L, Börjesson P. The prospects for an expansion of biogas systems in Sweden—incentives, barriers and potentials. Energy Policy.Elsevier; 2007.
[21] Börjesson, Pål. Bioenergi från jordbruket, SOU 2007-36, Attachment; 2007.
[22] Berglund M. Biogas from a Systems Analytical Perspective (PhD Thesis), LTH; 2006.
[23] Värmeforsk, Biogas-Nuläge och framtida potential; December 2006.
[24] SGC and Biomil AB. Sammanställnings och analys av potentialen för produktion av förnyelsebar metan (biogas och SNG) i Sverige; 2005.
[25] JTI. Biogaspotential och framtida anläggningar i Sverige; 1998.
[26] Swedish Environmental Protection Agency. Det framtida jordbruket, 2021. Slutrapport från systemstudien för ett miljöanpassat och uthålligt jordbruk, Naturvårdsverkets rapport nr 4755; 1997.
[27] Deublein D, Steinhauser A. Biogas from waste and renewable resources. Verlag GmbH & Co: Wiley-VCH; 2008.
[28] Swedish Board of Agriculture and Statistics of Sweden. Jordbruksstatistisk årsbok 2009 med data om livsmedel; 2009.
[29] Avfall Sverige. Svensk Avfallshantering; 2008.
[30] European Environmental Agency. Municipal waste generation per capita. Available from: http://www.eea.europa.eu/data-and-maps/figures/municipal-waste-generation-per-capita-in-western-europe-eu-15-new-member-states-eu-12-eu-countries-eu-27-and-total-in-europe-eu-27-turkey-croatia-norway-iceland-switzerland-3; June 15, 2011.
[31] Miljömålsportalen. Available from: www.miljomal.se; May 31, 2011.
[32] Basdata om biogas 2006, Svenskt Gastekniskt Center. Available from: www.energigas.se; 2011-11-20.
[33] Swedish Environmental Protection Agency. Sveriges miljömål. Available from: www.naturvardsverket.se; April 15, 2010.
[34] Länstyrelsen i Stockholms län. Miljömål. Available from: www.ab.lst.se; April 15, 2010.
[35] Stockholm Vatten VAAB, AnoxKaldnes AB. and WSP. Ökad biogasproduktion vid Henriksdals reningsverk. Available from: http://www.stockholmvatten.se/commondata/rapporter/avlopp/Biogas; 2009. 2011-06-17.
[36] Centro de Promoción de Tecnologías Sostenibles. Guía Técnica General de Producción Más Limpia. La Paz, Bolivia; 2005.

[37] Swedish Energy Agency, press release. Available from: http://energimyndigheten.se/sv/Press/Pressmeddelanden/Energimyndigheten-fordelar-41-miljoner-kronor-till-sex-nya-biogasprojekt/; July 30, 2011.
[38] Sanches Pereira Alessandro. Is bioenergy the big bad wolf in the forestry sector?: A discussion about the sustainable supply chain management role in bioenergy systems, Conference paper in World Renewable Energy Congress, Linköping; 2011.
[39] Murphy JD, Power NM. How can we improve the energy balance of ethanol production from wheat? Fuel Elsevier 2008;87:1799–806.
[40] Swedish Biogas International. Available from: http://www.swedishbiogas.com/us/reference-plants/sweden/norrkoeping; August 15, 2011.
[41] Holm Nielsen, JB, Oleskowicz-Popiel, P. The Future of Biogas in Europe: Visions and Targets until 2020. European Biogas Workshop and Study Trip, The Future of Biogas in Europe, University of Southern Denmark; 2007.
[42] Swedish Board of Agriculture. Husdjur i juni; 2008.
[43] Statistics Sweden and Swedish Board of Agriculture. Hästar och anläggning med häst 2004; 2005.
[44] OECD. Environmental Indicators for Agriculture – vol. 3: Methods and Results; 2001.
[45] Vafab Miljö. Växtkraft—Process description of the Biogas plant in Västerås. 2006. Available from: www.vafabmiljo.se; May 2, 2010.
[46] RVF, 2005:06 Utvärderingavstorskaliga system förkomposteringochrötning-avkällsorteratbioavfall, Bilaga 1a (Swedish: evaluation of large scale systems for composting and digestion of Biowaste sorted at source, Attachment 1a).
[47] Personal communication. Personal communication via email with Swedish biogas producing company who received budget offer for plant being planned; 2012. 2012-11-16.
[48] SGC. Rapport SGC 178 Biogasanläggningar med 300 GWh årsproduktion – system, teknikochekonomi (Swedish biogas facilities with 300 GWh yearly production, system, technology and economy); 2007.
[49] Maeng H, Lund H, Hvelplund F. Biogas plants in Denmark: technological and economic developments. Applied Energy 1999;64:195–206.
[50] LRF. Biobränslenas roll i ett uthålligt energisystem—Ett energiscenario från LRF; 1995.
[51] Energy Markets Inspectorate. Förändrade marknadsvilkor för biogasproduktion. EI R2010:17; 2010.
[52] Bioenergiportalen. Salix i kretsloppet. Available from: www.bioenergiportalen.se/attachments/42/407.pdf; 2011-06-17.
[53] Svärd Å, la Cour Jansen J.. Svenska biogasanläggningar, erfarenhetssammanställning och rapporteringssystem. Report 2003:14, Swedish Water Association; 2003.
[54] Bioenergitidningen, 2008. Available from: http://bioenergitidningen.se/files/resourcesmodule/@random46d6cce6d449a/1220270237_biodriv.pdf; 2011-10-30.
[55] Holm Nielsen, JB. Available from: http://www.ramiran.net/doc07/Biogas; August 10, 2011.
[56] Swedish Board of Agriculture. Available from: http://www2.jordbruksverket.se/webdav/files/SJV/trycksaker/Pdf_ovrigt/ovr147.pdf; 2011-10-30.
[57] Goldemberg J, Guardabassi P. The potential for first-generation ethanol production from sugarcane. Biofuels, Bioproducts & Biorefining 2009;4:17–24.
[58] AGA Sweden. Available from: www.aga.se; April 7, 2010.
[59] Energy Markets Inspectorate. Ökad andel biogas på en utvecklad gasmarknad, EI R2009:12; 2009.